NEW CONCEPT FOR ACCELERATION OF SLOW, LOW-CHARGE-STATE HEAVY ION BEAMS*

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Abstract

A modern post-accelerator for radioactive beam facilities requires acceleration of heavy ions beginning with charge state 1+ in order to maximize the intensity of the beams available for experiments. The acceleration of unstable nuclides with mass number up to 240 is required. For acceleration of low-velocity heavy ions very low-frequency RFQs are appropriate. However, the accelerating efficiency of such RFQs is low. To overcome this drawback we propose a hybrid accelerating structure that is formed by an alternating series of drift tubes (DTL) and RFQ sections. In such a structure the accelerating and focusing functions are decoupled. A hybrid RFQ (H-RFQ) operating at 12 MHz was designed for acceleration of heavy ion beams with q/A=1/240. The accelerating structure is ~3.3 m long and consists of three sections of DTL and two sections of RFQ. Each section of the DTL comprises 10 to 14 drift tubes. The RFQ sections comprise five $\beta\lambda/2$ cells and form a focusing triplet. The average accelerating gradient of the H-RFQ is about twice that of a conventional RFQ. This paper describes a complete study of beam dynamics in the new H-RFQ accelerating structure. A project to carry out a cold-model test of the H-RFQ will be pursued.

1 INTRODUCTION

The injector section of the Rare Isotope Beam (RIB) linac of the RIA facility requires acceleration of singly charged ions in the mass range from 6 to 240 [1]. Gas stripping of the heaviest ions takes place at ~20 keV/u. The efficient capture of an initially dc beam, maintaining low-emittance in longitudinal phase space and providing the initial acceleration can be performed using a multi-harmonic buncher and a RFQ [2]. Further highly efficient acceleration of well bunched ion beams will be performed in the proposed hybrid RFQ (H-RFQ) structure.

2 THE HYBRID RFQ CONCEPT

The acceleration of slow, low-charge-state heavy ion beams is a difficult problem. A device that can be utilized is a conventional RFQ accelerator. The rf electric fields of such devices are very effective at focusing heavy ions, but the longitudinal electric field provided only by the vane modulations makes it an inefficient accelerating structure. For low velocity ions the structure must operate at a low rf frequency leading to a very large and expensive structure.

IH-DTL structures have been developed and used for acceleration of ions with $q/m \geq 1/60$ in energy range above ~120 keV/u. They use a series of DTL accelerating sections each followed by independent DC magnetic triplets for focusing [3]. The magnetic triplets can be located either inside or outside the resonant tank. We found that the concept of separated accelerating and focusing zones can be applied to the acceleration of heavy ions with $q/m \geq 1/240$ and at much lower energies if the beam focusing is provided by rf quadrupoles. The DTL accelerating and rf focusing sections can be integrated into a single resonant structure we call the hybrid RFQ.

The use of rf quadrupoles for heavy ion beam focusing in 'triplet' mode is illustrated in Fig. 1. An unmodulated four-vane RFQ forms two sections each with length $\beta\lambda$ separated by a drift space $\beta\lambda/2$. The focusing strength of each RFQ lens with the length $\beta\lambda/2$ is adjusted and fixed by the aperture radius R_0. A section of the RFQ with length $\beta\lambda$ acts as a "doublet". The drift space between the "doublet" is necessary in order to ease the required electric field between the vanes. The whole focusing system works as a symmetric triplet. At higher q/m lower focusing gradients are required and it can be shown that in such cases the RFQ triplet can contain only three $\beta\lambda/2$ cells. A remarkable feature of the RFQ triplet is the lack of fringing field effects because the arrival time of beam bunches is synchronized to zero field at the edges of the RFQ vanes.

We have designed a CW H-RFQ for acceleration of singly-charged uranium in the front end of the RIB linac. For CW operation the peak surface field must be chosen very carefully. Our design is based on a 12 MHz accelerating structure with 100 kV between the drift tubes (DT) and RFQ vanes. The peak surface electric field occurs on the vanes of the first RFQ lens and it is 20% lower than in the existing 12 MHz RFQ structure [2]. The surface field on the drift tubes is kept even lower by selecting long accelerating gaps.

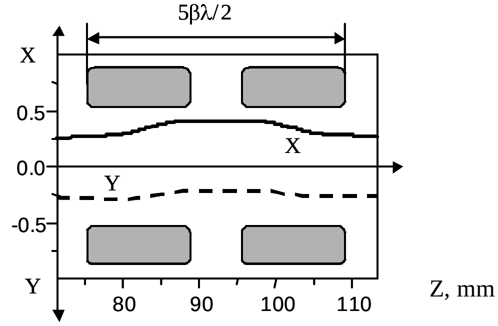

Figure 1: Focusing of axial-symmetric beam by RFQ triplet.

* Work supported by the U. S. Department of Energy under contract W-31-109-ENG-38.

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Basic design parameters of the H-RFQ are given in Table 1. Figure 2 shows beam energy vs. distance in the H-RFQ and in a conventional RFQ. The reference RFQ was designed at the same voltage and operating frequency with constant phase advance of transverse oscillations per period equal to 17°. As is seen from graph the H-RFQ provides twice as much accelerating voltage.

Table 1: Design parameters of the H-RFQ

Operating frequency	12.125 MHz
Ion species	^{6}He^{+1} to ^{240}U^{+1}
Beam energy	7 to 20 keV/u
Length	334 cm
Number of drift tubes in three sections	13-10-13
Drift tube aperture radius	1.0 cm
RFQ aperture radius	1.14-1.23 cm
Inter-vane inter-DT voltage	100 kV
RF power according to the code MWS	11.6 kW
Peak surface field	118 kV/cm

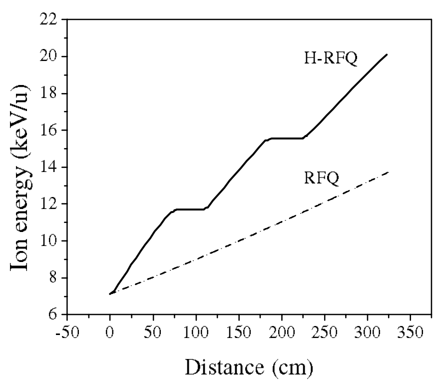

Figure 2: Beam energy as a function of longitudinal distance along the reference RFQ and H-RFQ.

3 BEAM DYNAMICS SIMULATION

The beam dynamics design of the H-RFQ structure iterated between the two steps: 1) preliminary design of the longitudinal layout and 2) detailed simulation of beam dynamics in 3D electric fields. These steps were iteratively repeated in order to achieve design goals; minimal emittance growth, lowest possible peak surface field, lowest sensitivity to the misalignments and rf field errors, and maximum possible 6D acceptance.

The simulations were done by ray tracing codes DYNAMION [4] and LANA [5] in 2D and 3D realistic electric fields. In the gaps between the drift tubes 2D electric fields were used. The 3D electric fields between the RFQ electrodes and neighboring drift tubes were simulated by SIMION 7 [6].

The input beam is formed by the multi-harmonic buncher and RFQ. These devices are optimized for the formation of the lowest possible longitudinal emittance. The 12 MHz RFQ upstream of the H-RFQ is a modification of the existing prototype [2] with redesigned vanes. The conventional RFQ following the multi-harmonic buncher is still the best option for the formation of lowest possible longitudinal emittance. This RFQ is designed for 92 kV inter-vane voltage with R_0=0.9 cm. In this very low velocity region the RFQ provides 1.2 MeV energy gain over the length 2.2 m. The beam phase space plots after the RFQ and matched to the entrance of the H-RFQ are shown in Fig. 3.

The first DT section of the H-RFQ operates at zero synchronous phase while the last two DT sections operate at –20° synchronous phase. The 1+ rare isotope beams come from either standard ISOL-type ion sources or a helium gas catcher and, therefore, the maximum expected transverse normalized emittance is quite low ~0.1 π·mm-mrad. Heavy beams such as uranium will be formed even with lower normalized emittances, ~0.01 π·mm-mrad. Figure 4 shows beam envelopes at the $\sqrt{5}\sigma$ -level in horizontal, vertical, phase and relative energy planes. The graphs are given for $\varepsilon_{n,\perp}$=0.03 π·mm·mrad and $\varepsilon_{n,||}$=0.1 π·keV/u·nsec.

Figure 5 presents emittance evolution along the H-RFQ for typical emittance values shown in Fig. 3. There is 7% rms transverse emittance growth due to the coupling of transverse and longitudinal motion in the radially non-uniform electric fields. The 100% transmission transverse acceptance of the H-RFQ is 0.2 π·mm-mrad which is twice the maximum beam emittance expected for light exotic ions. The decrease of longitudinal emittance is caused by the beam filtration that is still necessary after the multi-harmonic buncher and RFQ section. The total capture efficiency from the initially DC beam is 80% within a 5σ longitudinal emittance $\varepsilon_{n,||}$=0.1 π·keV/u·nsec.

The simulations show that the beam parameters such as average energy, phase spread, emittances, Twiss parameters, etc. experience negligible change if the voltage is varied in the range -3% to +7% from the nominal value.

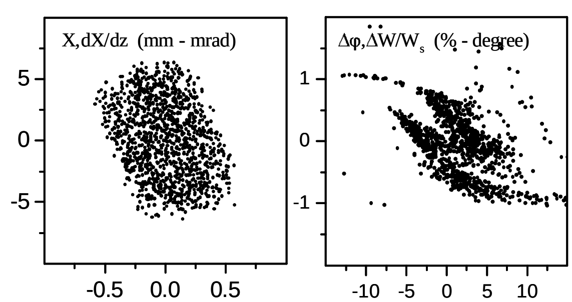

Figure 3: Phase space plots at the entrance of the H-RFQ.

4 H-RFQ RESONANT STRUCTURE

Several resonant structures have been considered as candidates for the H-RFQ. The main specifications for our application are: 1) the structure length ~3.34 m is determined by the given input and output beam energies; 2) the structure should be mechanically stable; and 3) the shunt impedance should be high. Though split-coaxial structures have been used in several low frequency RFQs, the Wideroe-type structure better satisfies the abovementioned conditions. In fact, this type of structure was considered as a potential candidate for 12.5 MHz

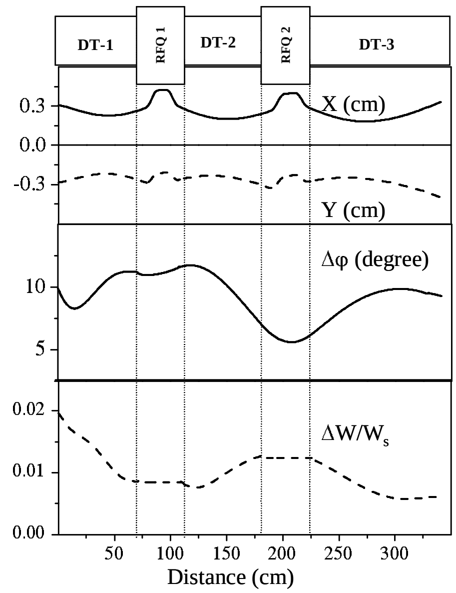

Figure 4: Beam envelopes along the H-RFQ

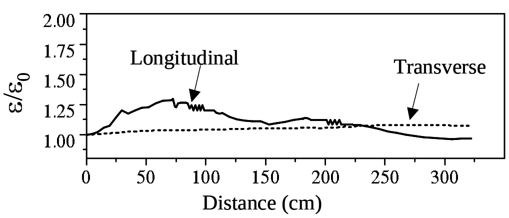

Figure 5. Relative emittance evolution.

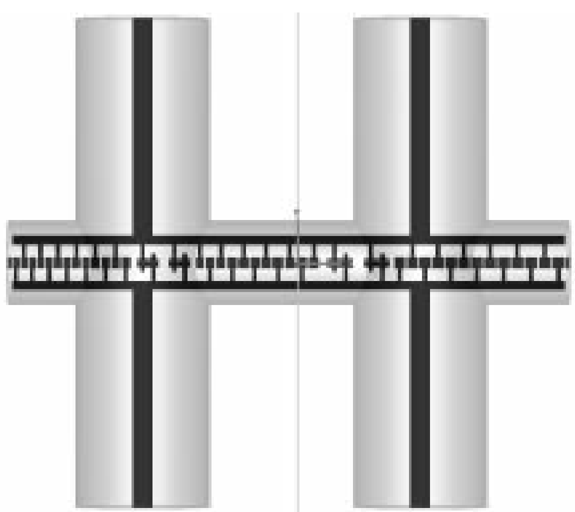

Figure 6: Side view of the H-RFQ resonant structure.

RFQ at Argonne National Laboratory (ANL) [7]. The side view of the accelerating structure used for the electrodynamics simulation by the code Microwave Studio (MWS) [8] is shown in Fig. 6. According to MWS the rf losses are 11.6 kW at 100 kV inter-vane voltage in this copper cavity. The losses are lower than in split-coaxial RFQ of similar length because the total capacitive loading of the drift tubes is about half that of the four-vane structure. Due to the short length of the structure compared to the wavelength, a uniform voltage distribution on all vanes and drift tubes is expected, as shown in Fig. 7.

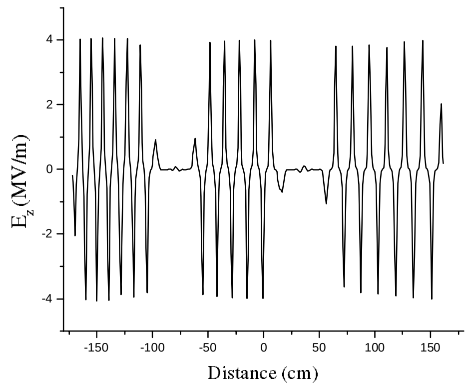

Figure 7: Distribution of the longitudinal component of electric field along the structure as calculated by MWS.

5 CONCLUSION

The proposed hybrid RFQ structure has the following innovative features compared to conventional RFQs with similar parameters: a) separate sections of drift tube accelerator and rf focusing structures placed inside the same resonant structure producing twice the accelerating gradient; b) focusing provided by four rf quadrupoles operating as a triplet; c) lower rf power consumption per unit length; d) lower peak surface electric fields and less surface area at high electric field.

A cold model of the H-RFQ for the RIA RIB linac is under development. The H-RFQ can be used for effective acceleration of low velocity heavy ions in various fields of application, where focusing by electric fields is appropriate.

6 ACKNOWLEDGEMENT

The authors would like to thank J.A. Nolen for valuable remarks and discussions.

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